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Bureau des programmes solaires

DRYAIR
VERSION 1.0

USER'S MANUAL

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Assistance and Information

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NOMENCLATURE

A	total collector area
A_c	area of one collector
A_{fm}	surface area of fibre matrix
A_D	drying area of material
b	spacing between upper and lower absorber plates
C_p	specific heat
C_{p_a}	specific heat of air
C_{p_e}	effective specific heat of air
C_{p_w}	specific heat of water
E_{hx}	effectiveness of heat exchanger
F'	$U_o/(U_o + U_L)$
F_R	collector heat removal factor
$F_R\tau\alpha$	collector transmission-absorption coefficient
$F_R U_L$	collector heat loss coefficient
H	measured hourly solar radiation
H_b	beam hourly solar radiation
H_{bT}	beam hourly solar radiation on a tilted surface
H_d	diffuse hourly solar radiation
H_{dT}	diffuse hourly solar radiation on a tilted surface
H_{ex}	extraterrestrial hourly solar radiation
h_{fg_d}	latent heat of vapourization at the dry bulb temperature
h_{fg_w}	latent heat of vapourization at the wet bulb temperature
h_d	mass transfer coefficient
h_{ai}	enthalpy of air
h_{pf}	plate to fluid convective heat transfer coefficient
h_r	radiative heat transfer coefficient
H_r	reflected hourly solar radiation
H_T	solar radiation on the tilted surface
I	total incident solar radiation
k	conductivity of air
K	incidence angle modifier
K_T	clearness index

L	length of drier
L	length of collector in flow direction
$\dot{m}$	mass flow rate
$\dot{m}_a$	mass flow rate of air
$\dot{m}_D$	mass flow rate of dry material
m_D	mass of material
M_D	equilibrium moisture content based on dry weight
M_W	equilibrium moisture content based on wet weight
n	number of air flow passage channels
N	day number of the year
Nu	Nusselt Number
Pr	Prandtl Number
Q_{heat}	energy output from heater
Q_S	solar heating contribution
Qu	useful heat obtained from collector
R	drying rate
R_b	ratio of beam radiation on tilted surface to horizontal surface
R_e	Reynolds Number
s	collector slope
S_c	solar constant
T_1, T_2	temperature of upper and lower plates of the air channel
T_a	ambient temperature
Ta_d	dry bulb ambient temperature
Ta_w	wet bulb ambient temperature
T_{ave}	average temperature that collector losses heat from
T_{co}	collector outlet temperature
T_{d_i}	inlet temperature to drier
T_{do}	temperature of air leaving drier
T_{fi}	collector fluid inlet temperature
T_{fm}	average collector fluid temperature
T_{hx_o}	temperature out of heat exchanger
T_{plate}	average temperature of the collector absorber plate
U_L	collector heat loss coefficient
U_o	total plate to fluid heat transfer coefficient

W	humidity ratio of air
W_{ai}	humidity ratio for outside air
W_{ao}, W_o	outlet humidity ratio
W_{ai}, W_i	inlet humidity ratio
W_c	critical humidity ratio
W_{s_w}	saturated humidity ratio at the wet bulb temperature
x	matrix constant
x_e	equilibrium moisture content
x_f	desired final moisture content of material
x_i	initial moisture content of material based on dry weight
y	matrix constant

Greek Symbols

α	solar absorptivity
δ	solar declination
γ	azimuth angle
ϕ	latitude
π	3.14159
μ	absolute viscosity
ρ	density
σ	Stefan-Boltzman constant
ω	hour angle
$\tau\alpha$	transmission-absorption product
$(\tau\alpha)_e$	effective transmission-absorption product

1. INTRODUCTION

The DRYAIR computer program was developed by Enermodal Engineering Limited to simulate the performance of air-based solar collectors to dry crops or other materials. The program can accept data of all PUSH approved air-based collectors (Amherst 200, Solartech Solair, and Watershed A-100) and any other parallel plate air-based collector.

DRYAIR is the only general computer program capable of simulating drying of a wide variety of crops or materials using air-based solar collectors. Performance calculations use a one hour time step to ensure maximum accuracy.

The program does, however, have several restrictions. First, it is limited to continuous drying processes, as opposed to batch drying. That is, the total moisture content of the material in the drier must be relatively constant. (In a batch process the total material moisture content is constantly decreasing.) Second, the user must know the drying characteristics of the material (e.g. equilibrium moisture content and critical moisture content) and of the drier (e.g. moisture removal rate at test conditions).

The mechanisms governing the rate of material drying are extremely complex. Although the solar collector energy output can be estimated fairly accurately, the user should expect deviations between the predicted and actual quantities of material dried. The DRYAIR computer program will provide a reasonable estimate of the thermal performance of solar drying systems provided that the user supplies system parameters within the program limitations. All users should read and understand this manual before using the program.

1.1 Introduction to Crop/Material Drying

Drying of materials is necessary in many industrial and agricultural processes. To prevent spoilage many crops must be dried including corn, wheat, sugar cane etc. Many foodstuffs are dried for long term storage or for

transportation including milk, flour, eggs, etc. Drying is also a critical step in many industrial processes. Materials that require drying include leather, fibres, paper and wood.

The rate of drying is dependent on the drier design. Drier designs can be divided into two general types: continuous and batch. In batch driers, the drier is filled with wet material and not emptied until all of the material reaches the desired minimum moisture content. In continuous driers, as material reaches the desired minimum moisture content it is removed and wet material added. Material need not be removed continuously but often enough that the total moisture content of the material in the drier stays relatively constant.

In batch driers the drying rate is constantly changing because the average moisture content of the material in the drier is changing. The rate of change in the drying rates is so variable that it is almost impossible to predict (1). For this reason batch driers are not handled by the DRYAIR program.

Continuous driers can be subdivided into three types: counter-flow, cross-flow and parallel-flow (similar to heat exchanger types). In counter-flow driers, air and material flow in parallel but opposite directions. In parallel-flow driers, air and material flow in the same direction. Air and material flow in perpendicular directions in a cross-flow drier. Like heat exchangers, a counter-flow arrangement is the most efficient and parallel-flow the least efficient. Because of the inefficiency of parallel-flow driers they are not handled by the DRYAIR program.

Besides the drier design, the drying rate is dependent on the relative humidity of the air. Relative humidity is the ratio of the weight of water in the air to the maximum weight of water that the air can hold (saturated conditions). The greater the relative humidity is the lower the drying rate is. The drying rate will continue to decrease as the relative humidity increases

until the relative humidity of air is equal to the relative saturation of the material. At this condition, referred to as the equilibrium moisture content of the material, no moisture is transferred. The value of the equilibrium moisture content depends on the material, the relative humidity of the air and to a lesser extent temperature.

The most common method of decreasing the relative humidity (increasing the drying rate) is to heat the air. The more the air is heated, the greater the drying rate is. For most crops and materials, however, there is an upper limit on the inlet air temperature above which the crop or material may crack.

2. THE DRYAIR COMPUTER PROGRAM

2.1 System Operation

A typical air-based solar crop/material drying system is shown in Figure 1. The system consists of air-based solar collectors, fan, auxiliary heat and material drier. The operation of this system is quite simple. When the drier is operating, outside air is brought in the air inlet. If a heat exchanger is placed before the collector, heat from the drier exhaust is transferred to the outdoor air. The air then passes through the collectors (even if the sun is not shining) to be heated by solar energy. If the air leaving the collector is too hot, then the air flow through the collector is reduced and outside air is mixed with the collector outlet air. If the heat exchanger is placed after the collector, heat from the drier exhaust is transferred to the air. The air then passes through the heater. There are two types of heater: constant temperature and constant energy input. For the constant temperature heater the outlet temperature is controlled at a constant value. Conversely, the constant energy input heater would have a variable temperature, fluctuating with the collector outlet temperature.

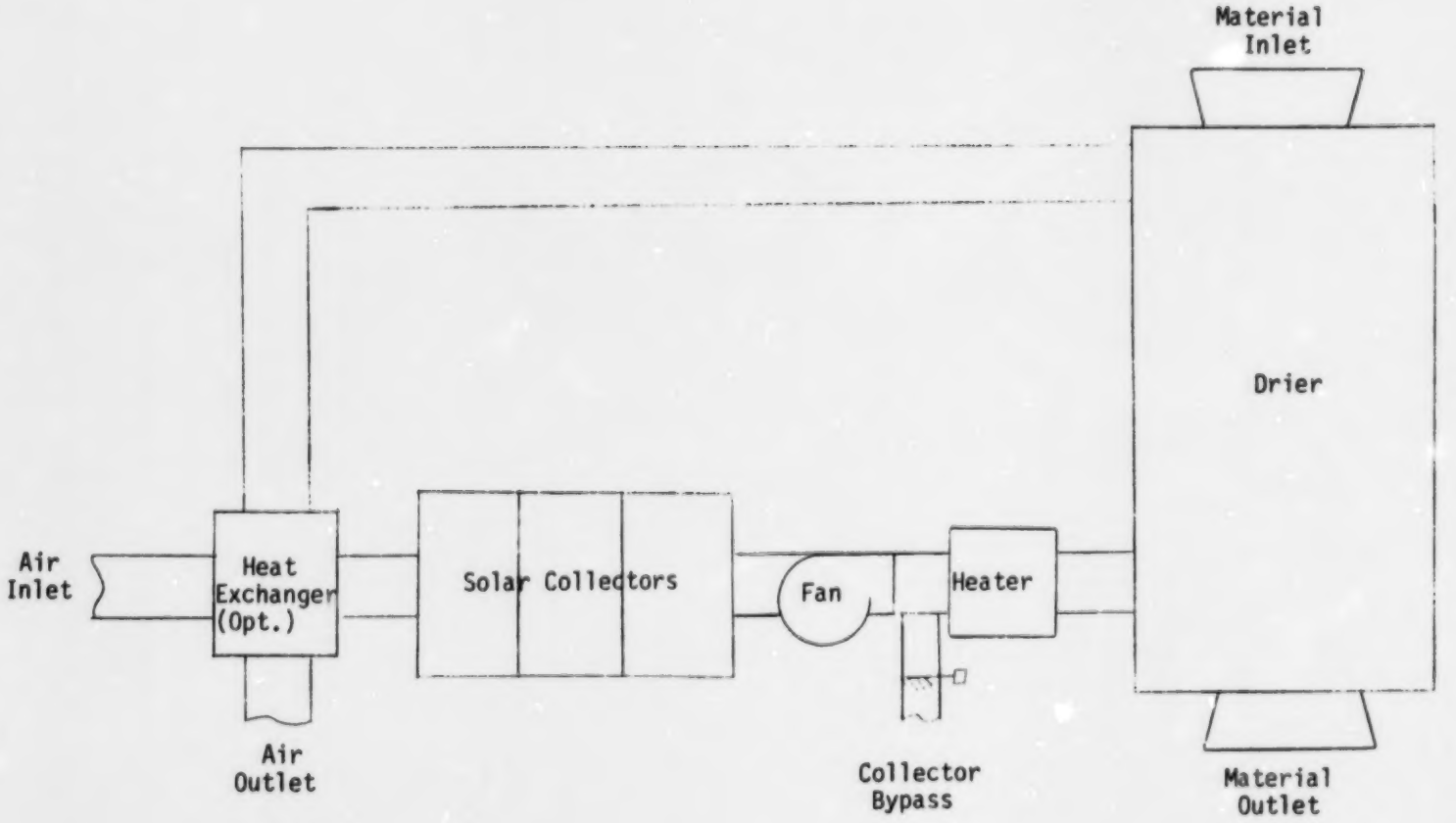
The hot dry air passes through the drier picking up moisture from the material. As the material is dried to the desired condition it is removed and wet material added.

2.2 Using the DRYAIR Program

Using the DRYAIR computer program is relatively easy. The program has been written so that the user enters the system description interactively with the computer. The program makes some fundamental checks on the suitability of the input parameters. If a parameter appears unrealistic, a warning is printed although the program accepts the value.

Before the program can be run hourly weather data (solar radiation on a horizontal surface, dry bulb and wet bulb temperatures) must be available. This data can be obtained from Atmospheric Environment Service. The first step in the program execution is to calculate solar radiation on the collector

Figure 1: Typical Solar Material Drying System (Counter-Flow)



surface and store it in a scratch file. During the simulation the program accesses the scratch file. If collector slope and orientation remain the same on successive runs, the same scratch file is used. If the values are changed, the scratch file is automatically recalculated.

When the user accesses the program, a series of questions concerning the program will have to be answered. These questions are shown in Section 2.3. When the questions have been answered, the user has the choice of several commands: C or CHANGE

D or DEFAULT

L or LIST

M or MODIFY

R or RUN

S or STOP

T or TITLE

The use of these commands is discussed below.

CHANGE this command is used to change the program input data. A list of the input data and their meanings is given in Section 3.1. The command is of the form

C or CHANGE Parameter # = New Value

e.g. C C3 = 50

Several changes can be made on one line with or without the equal sign

e.g. C C4 = 0.0, T1 3

DEFAULT this command is used to re-initialize all the input parameters to their default values. There are no options with this parameter.

LIST this command is used to list either all the input parameters, all the parameters of one section or an individual parameter.

L or LIST ALL - lists all parameters

L C - lists all collector parameters

L C3 - lists collector slope

MODIFY this command is used to modify the default collector characteristics i.e. to change the collector type.

RUN this command is used to run the program. If the option "P" is used a copy of the output will be sent to the printer. If a simulation period other than one year is required, the first day of the simulation followed by the length of the simulation should be entered

e.g. RUN or R P 31,28 - this would execute the program starting January 31st and run for 28 days. A copy of the output would be sent to the printer.

2.3 Tutorial Session

```
**********************************
*                                *
*            DRYAIR              *
*      VERSION 1.0  JUNE,1983    *
*                                *
**********************************

DO YOU WISH INSTRUCTIONS? (Y/N) : N
 IS PROCESSED WEATHER DATA AVAILABLE (Y/N) ?N
 ENTER CITY NAME : OTTAWA
 ENTER LATITUDE OF CITY (DEG.) : 45.5
 ENTER SOLAR COLLECTOR TYPE :
    1 - ZOMEREX 200
    2 - SOLARTEC H SOLATR
    3 - WATERSHED A100
    USE ZERO FOR A PARALLEL PLATE COLLECTOR NOT
    LISTED ABOVE 0

C.D.L.M.R.S.T.?: C C1 25. M3 15.
THE NUMBER OF CHANGES MADE =   2

C.D.L.M.R.S.T.?: L M

M.              MATERIAL DRYING CHARACTERISTICS

 M1   % EQUIL. MOISTURE CONTENT AT 10 RH AIR (DRY WT.)      3.00
 M2   % EQUIL. MOISTURE CONTENT AT 70 RH AIR (DRY WT.)     10.00
 M3   % CRITICAL MOISTURE CONTENT (DRY WT.).............   15.00
 M4   SPECIFIC HEAT OF DRY MATERIAL (KJ/(KG*C))........     2.00

C.D.L.M.R.S.T.?: L C1
C1   NUMBER OF COLLECTORS.....................  .........   25.00

C.D.L.M.R.S.T.?: T SAMPLE RUN

C.D.L.M.R.S.T.?: RUN 18.60

    * WITH THE GIVEN TEST CONDITIONS THE COLLECTOR HAD AN FR OF  .62
      UNDER THE SAME CONDITIONS THE PROGRAM CALCULATES AN FR OF  .61
```

**** DRYAIR INPUT DATA ****

SAMPLE RUN

SIMULATION PERIOD - FIRST DAY :180 LAST DAY :239

C. COLLECTOR DATA

C1	NUMBER OF COLLECTORS	25.00
C2	NUMBER OF COLLECTORS IN SERIES	1.00
C3	COLLECTOR SLOPE (DEGREES)	45.00
C4	COLLECTOR ORIENTATION (SOUTH=0,EAST=+, DEG.)	.00
C5	COLLECTOR FLOW RATE PER UNIT AREA (L/(SEC*M2))	10.00
C6	FAN POWER CONSUMPTION PER UNIT AREA (W/M2)	10.00

T. COLLECTOR TEST DATA

T1	GROSS AREA OF ONE COLLECTOR (M2)	2.00
T2	NUMBER OF COLLECTORS IN SERIES WHEN TESTED	1.00
T3	FR-TAU-ALPHA (TEST)	.50
T4	FR-UL (W/(M2*C)) (TEST)	4.00
T5	INCIDENT ANGLE MODIFIER	-.10
T6	COLL. TEST FLOW RATE PER UNIT AREA (L/(SEC*M2))	10.00
T7	TRANSMISSION-ABSORPTION PRODUCT	.90
T8	RATIO OF APERTURE TO GROSS AREA	.90
T9	COLLECTOR CHANNEL HEIGHT (MM)	6.00
T10	COLLECTOR FLOW CHANNEL LENGTH PER COLLECTOR (M)	1.00

M. MATERIAL DRYING CHARACTERISTICS

M1	% EQUIL. MOISTURE CONTENT AT 10 RH AIR (DRY WT.)	3.00
M2	% EQUIL. MOISTURE CONTENT AT 70 RH AIR (DRY WT.)	10.00
M3	% CRITICAL MOISTURE CONTENT (DRY WT.)	15.00
M4	SPECIFIC HEAT OF DRY MATERIAL (KJ/(KG*C))	2.00

L. DRYING LOAD DATA

L1	MASS OF MATERIAL TO BE DRIED (KG-DRY/DAY),0=MAX.	.00
L2	% INLET MOISTURE CONTENT (KG-WATER/KG-DRY MAT.)	70.00
L3	INLET TEMPERTURE OF MATERIAL (C)	20.00
L4	% OUTLET MOISTURE CONTENT (KG-WATER/KG-DRY MAT.)	20.00
L5	NUMBER OF DAYS OF OPERATION PER WEEK	7.00
L6	HOURS OF OPERATION PER DAY, 0=REQUIRED TIME	9.00
L7	STARTING HOUR FOR DRYING OPERATION	8.00

D. DRIER CHARACTERISTICS

D1	DRIER DESIGN : 1 - COUNTER-FLOW, 2 - CROSS-FLOW	1.00
D2	TYPE : 1-CONSTANT ENERGY INPUT, 2-CONSTANT TEMP.	2.00
D3	MAXIMUM AIR INLET TEMPERATURE (C)	30.00
D4	IF D2=1, AUX. HEATER OUTPUT (KW)	10.00
D5	DRIER H.X. LOCATION 0=NONE,1-BEFORE,2-AFTER COL.	.00
D6	EFFECTIVENESS OF DRIER HEAT EXCHANGER	.00
D7	DRIER TEST FLOW RATE (M3/S)	1.00

D8 DRIER TEST INLET TEMPERATURE (C)..... 20.00
D9 TEST INLET RELATIVE HUMIDITY (%)..... 20.00
D10 TEST OUTLET RELATIVE HUMIDITY (%)..... 70.00

CITY DATA

LOCATION .....OTTAWA
LATITUDE OF LOCATION (DEG.)..... 45.5

MODIFIED COLLECTOR CHARACTERISTICS

FRTA - ADJUSTED = .56
FRUL - ADJUSTED = 4.00 W/M2-C)

DRIER TEST CONDITIONS

WET BULB TEMPERATURE (C) : 9.2
HUMIDITY RATIO IN (KG-W/KG-A) :.0029
HUMIDITY RATIO OUT (KG-W/KG-A) :.0061
RATE OF WATER REMOVAL (KG-W/HOUR) : 14.0
MATERIAL ENTERING RATE (KG/HOUR) : 38.1
EFFICIENCY OF DRIER (%) : 77.15

PERFORMANCE PREDICTION

MON	SOLAR AVAIL. (GJ)	SOLAR COLLEC (GJ)	AUX. ENERGY (GJ)	HEATING LOAD (GJ)	FAN POWER (GJ)	MASS DRIED (KG)
JAN	2.264	.064	.000	.064	.032	-103.
JUL	28.694	4.599	.33	5.202	.502	3077.
AUG	25.273	4.256	.005	5.141	.437	3177.
YR	54.14	8.91	.54	10.52	.97	6901.

ENERGY SAVINGS DUE TO SOLAR (GJ) : 8.11

ENERGY SAVINGS DUE TO SOLAR (%) : 76.14

AVERAGE SOLAR SYSTEM COLLECTION EFFICIENCY (%) : 14.26

SOLAR CONTRIBUTION PER SQUARE METRE (GJ/M2) : .160

C.D.I.M.R.S.T.? 9

3. SYSTEM INPUT PARAMETERS

The following sections describe the parameters used in the DRYAIR computer program. The default value for each parameter is included with the definition.

3.1 Definition of Input Parameters

There are five separate sections of input data:

C - collector data
T - collector test data
M - material drying characteristics
L - drying load data
D - drier characteristics

The parameters for each of these sections are discussed below.

Collector Data

C1 NUMBER OF COLLECTORS (2)

The number of collectors in the solar heating system.

C2 NUMBER OF COLLECTORS IN SERIES (1)

The number of collectors that are connected in series as opposed to parallel.

C3 COLLECTOR SLOPE (DEGREES) (45)

The angle that the collector is tilted from the horizontal in degrees. This parameter must be between 0 and 90. If this parameter is different from the value on the scratch weather file, the weather data will automatically be reprocessed.

C4 COLLECTOR ORIENTATION (SOUTH=0 EAST=+, DEG)(0)

The number of degrees that the collector is oriented off due south (east is positive, west is negative). This parameter must be between -90 and 90. If this parameter is different from the value on the scratch weather file, then the weather data will automatically be reprocessed.

C5 COLLECTOR FLOW RATE PER UNIT AREA (L/(SEC*M2) (10)

The air flow rate per unit collector area through the collectors for the proposed system in litres per sec per square metre of collector. Note: This is also the flow rate through the drier.

C6 FAN POWER CONSUMPTION PER UNIT AREA (W/M2) (10)

The incremental energy required to operate the collector fan in watts per square metre of collector. This should not include the fan power that would be required to circulate the air if there was no solar heating system.

Collector Test Data

The program contains test results for three air-based solar collectors (effective Jan. 24, 1983): Amherst 200, Solartech Solair and Watershed A-100. These test results can be updated or other test results added.

T1 GROSS AREA OF ONE COLLECTOR (M2) (2)

The gross or outside area of one collector in square metres.

T2 NUMBER OF COLLECTORS IN SERIES WHEN TESTED (1)

Number of collectors connected in series when it was tested, typically one.

T3 FR-TAU-ALPHA (TEST) (0.5)

The $F_R(\tau\alpha)_e$ of the collector when tested by a certified laboratory (based on gross collector area).

T4 FR-UL (W/M²C*)(TEST) (4.0)

The $F_R U_L$ of the collector when tested by a certified laboratory (based on gross collector area) in W/(m² °C).

T5 INCIDENT ANGLE MODIFIER (-0.1)

Coefficient that reduces collector solar transmission for incident angles off the normal. The value for this coefficient, b_o, is obtainable from collector data sheets and is usually negative. If test results are not available use -0.10 for single glazed collectors and -0.17 for double glazed collectors.

T6 COLL. TEST FLOW RATE PER UNIT AREA (L/SEC*M2) (10.)

The air flow rate through the collector at test conditions in litres per second per square metre of collector.

T7 TRANSMISSION-ABSORPTION PRODUCT (0.9)

The $(\tau\alpha)$ effective of the collector. This can be estimated as 1.01 times $\tau\alpha$ for a single glazed collector where τ is the glazing solar transmission and α is absorber solar absorptivity.

T8 RATIO OF COLLECTOR APERTURE TO GROSS AREA (0.9)

The ratio of the collector aperture area (i.e. window area) to the gross area. Typically this value is usually close to 0.9, actual values can be obtained from collector data sheets.

T9 COLLECTOR FLOW CHANNEL HEIGHT (MM) (6)

The spacing between the upper and lower absorber plates in millimetres. For a curved upper absorber use the average spacing. In general decreasing the flow channel height increases the collector F_R although this will result in a higher collector pressure drop.

T10 COLLECTOR FLOW CHANNEL LENGTH PER COLLECTOR (M) (1)

The distance or length that the air stream is in contact with the absorber plate for one collector. In most collectors this will be the length of collector in the flow direction. In some cases, however, collectors are designed so that the collector length is much shorter than the collector such as in the overlapped glass plate collector.

Material Drying Characteristics

Typical values for these parameters are given in Section 3.3.

M1 % EQUIL MOISTURE CONTENT AT 10 RH AIR (DRY WT.)

Percentage of material that is water when at equilibrium with air at 10% relative humidity based on dry weight (see Section 3.3).

M2 % EQUIL MOISTURE CONTENT AT 70 RH AIR (DRY WT.)

Percentage of material that is water when at equilibrium with air at 70% relative humidity based on dry weight (see Section 3.3).

M3 % CRITICAL MOISTURE CONTENT (DRY WT.)

Percentage moisture content at which the drying rate begins to decrease based on dry weight (see Figure 4). If no information is available a conservative estimate would be to use the equilibrium moisture content at 100% relative humidity air (see Section 3.3).

M4 SPECIFIC HEAT OF DRY MATERIAL (KJ/(KG*C)) (2.)

Specific heat of the dry material, i.e. no water content.

Drying Load Data

L1 MASS OF MATERIAL TO BE DRIED (KG/DAY) (0 = MAX)

Mass of material based on dry weight to be dried per day. The system will operate as long as required to dry this quantity. If zero is entered, the amount of material that can be dried in the time specified is calculated.

L2 % INITIAL MOISTURE CONTENT (KG-WATER/KG-DRY MAT.)

Initial percentage of material that is water based on dry weight.

L3 INLET TEMPERATURE OF MATERIAL (C) (20.)

The average temperature of the material when it is added to the drier.

L4 % FINAL MOISTURE CONTENT (KG-WATER/KG-DRY MAT.)

Final or desired percentage of material that is water based on dry weight.

L5 NUMBER OF DAYS OF OPERATION PER WEEK

Number of days per week that the drier operates.

L6 HOURS OF OPERATION PER DAY, 0 = REQUIRED TIME

The number of hours per day that the drier is to operate. If zero is entered, the number of hours required to dry the amount of material specified in L1 is calculated.

L7 STARTING HOUR FOR DRYING OPERATION

The first hour that the drier is to operate, where 0=midnight, 8=8:00 A.M., 16=4:00 P.M.

Drier Characteristics

D1 DRIER DESIGN: 1 - COUNTER FLOW, 2 - CROSS FLOW (1)

The design of the drier.

D2 DRIER TYPE: 1 - CONSTANT ENERGY INPUT, 2 - CONSTANT TEMP. (2)

The type of heater used in the drier: either constant drier inlet temperature (electric) or constant heat (gas or oil).

D3 MAXIMUM AIR INLET TEMPERATURE (C) (30)

The desired drier inlet temperature if D2 is = 2, or the maximum allowable temperature before the heater will shut off if D2 = 1.

D4 IF D2 = 1, AUX. HEATER OUTPUT (KW) (10)

The output from the auxiliary heater. If D2=2 this parameter is not used.

D5 DRIER H.X. LOCATION 0 = NONE, 1 - BEFORE, 2 - AFTER COLLECTOR (0)

Location of drier heat exchanger where 0 indicates no heat exchanger is used, 1 - the heat exchanger is before the collectors, 2 - the heat exchanger is after the collectors. Note: it is possible to have a negative solar contribution if the heat exchanger is before the collectors since heat recovered by the heat exchanger could be lost by the collector.

D6 EFFECTIVENESS OF DRIER HEAT EXCHANGER (0.)

The effectiveness or efficiency of the heat exchanger used to reclaim heat from the drier exhaust to preheat outside air entering the drier. This parameter is normally less than 0.8.

D7-D10 These parameters describe the performance of the drier. These parameters must be for the material and moisture contents given in Section M and L2, L3 and L4.

D7 DRIER TEST FLOW RATE (M3/S) (1.)

The flow rate that the drier was tested at. It need not be the same as the proposed system flow rate (see parameter C5).

D8 DRIER TEST INLET TEMPERATURE (C) (20)

The inlet temperature to the drier when it was tested (not the dry bulb temperature).

D9 TEST INLET RELATIVE HUMIDITY (%) (20)

The relative humidity of the air at the drier inlet.

D10 TEST OUTLET RELATIVE HUMIDITY (%) (70)

The relative humidity of the air at the outlet from the drier (before the heat exchanger).

3.2 Weather Data

At present there is weather data for 46 cities that can be used by the program. These cities are tabulated below. The solar radiation data as supplied by Atmospheric Environment Service is of two types: derived or measured. Measured data is as recorded by their monitoring equipment (with missing data estimated from the previous day's values). Derived data is predicted by using other meteorological data such as rainfall, cloud cover etc.

City	Province	Latitude (Deg.)	Year	Solar Rad. Derived/Measured
Victoria	B.C.	48.7	1971	D
Prince George	B.C.	53.9	1974	M
Vancouver	B.C.	49.2	1971	M
Summerland	B.C.	49.6	1971	D
Frobisher Bay	N.W.T.	63.8	1975	D
Resolute	N.W.T.	74.7	1971	M

Edmonton	Alta.	53.6	1971	M
Medicine Hat	Alta.	50.0	1971	D
Uranium City	Sask.	59.6	1971	D
Swift Current	Sask.	50.3	1971	D
Saskatoon	Sask.	52.2	1971	D
Churchill	Man.	58.8	1975	D
Brandon	Man.	49.9	1971	D
Winnipeg	Man.	49.9	1971	M
The Pas	Man.	53.8	1971	M
Thunder Bay	Ont.	48.4	1971	D
Sault Ste. Marie	Ont.	46.5	1971	D
Sudbury	Ont.	46.5	1971	D
Kapukasing	Ont.	49.4	1966	M
Kingston	Ont.	44.2	1971	D
Muskoka	Ont.	45.0	1971	D
Windsor	Ont.	42.3	1971	D
London	Ont.	43.0	1971	D
Toronto	Ont.	43.7	1971	M
Ottawa	Ont.	45.4	1971	M
Montreal	Que.	45.5	1971	M
Sept Iles	Que.	50.2	1974	M
Quebec	Que.	46.8	1971	D
Sherbrooke	Que.	45.4	1971	D
Riviere du Loop	Que.	47.8	1971	D
Bagotville	Que.	48.3	1971	D
Val D'Or	Que.	48.0	1971	D
Fredericton	N.B.	45.9	1971	M
Charlo	N.B.	48.0	1971	D
Chatham	N.B.	47.0	1971	D
Moncton	N.B.	46.1	1971	D
St. John	N.B.	45.3	1971	D

Charlottetown	P.E.I.	46.3	1971	D
Truro	N.S.	45.4	1971	D
Halifax	N.S.	44.7	1971	M
Sydney	N.S.	46.2	1971	D
Yarmouth	N.S.	43.8	1971	D
St. John's	Nfld.	47.6	1971	M
Gander	Nfld.	49.0	1971	D
Stephenville	Nfld.	48.5	1971	D
Goose	Nfld.	53.3	1971	M

3.3 Drying Properties of Materials

Table 3.1 contains typical drying properties of several crops and foodstuffs. If the user has drying information on the particular material, this should be used instead of the data in the table. This data is extracted from reference 2 and the ASHRAE Handbook of Fundamentals (1977) Chapter 10 and is for a material temperature of approximately 25°C. The effect of temperature on these properties is shown in the Appendix for several grains.

MAP
Canadian Weather Stations
Resolute
Frobisher Bay
Uranium City
Churchill
Prince George
Edmonton
Vancouver
Victoria
Summerland
Saskatoon
The Pas
Medicine Hat
Swift Current
Brandon
Winnipeg
Kapuskasing
Thunder Bay
Goose Bay
Gander
St. John's
Stephenville
Sept Iles
Riviere du Loup
Bagotville
Quebec
Val d'Or
Charlo
Chatham
Fredericton
Saint John
Sydney
Charlottetown
Moncton
Truro
Halifax
Yarmouth
Sherbrooke
Montreal
Sault Ste. Marie
Sudbury
Ottawa
Muskoka
Kingston
Toronto
London

Table 3.1: Drying Characteristics of Materials (at 25°C)

	Equilibrium Moisture Content (%) based on dry weight[1]		
	with 10% R.H.	with 70% R.H.	with 100% R.H.
Crops			
Corn, yellow dent	4.6	16.4	28.0
Flaxseed	5.3	17.6	25.0
Sorghum	5.8	16.6	21.0
Soybean	3.3	16.4	20.0
Wheat	6.9	15.5	23.0
Foodstuffs			
White bread	0.5	11.1	23.5
Flour	2.6	12.4	22.8
Starch	2.2	9.2	14.8
Gelatin	0.7	7.6	13.5
Materials			
Cotton, American cloth	2.6	8.1	18.6
Cotton, Absorbent	4.8	22.8	27.3
Wool, Australian	4.7	17.2	26.9
Silk, raw	3.2	11.9	22.3
Linen, dry spun yarn	3.6	9.8	16.4
Hemp, manila and sisal	2.7	11.6	17.8
Rayon, Vicose nitro-cellulose	4.0	12.4	18.2
Rayon, cellulose acetate	0.8	3.6	6.3
Paper, M.f. newsprint	2.1	7.2	12.5
Paper, white bond	2.4	8.8	15.6
Paper, kraft wrapping	3.2	10.5	17.2
Leather, sole oak-tanned	5.0	20.6	34.4
Rubber, solid tires	0.11	0.76	1.1
Wood, timber	3.0	14.0	26.5
Soap, white	1.9	16.1	27.8
Tobacco, cigarette	5.4	25.0	66.5
Asbestos fiber, finely divided	0.16	0.62	0.95
Activated charcoal, steam activated	7.1	30.0	34.3
Sulfuric acid, H_2SO_4	33.0	67.0	91.5

1 The percentage equilibrium moisture content based on dry weight can be calculated from the equilibrium moisture content based on wet weight.

$$M_D = 100\ (M_w)/(100 - M_w)$$

4. DESCRIPTION OF PROGRAM OUTPUT

4.1 Thermal Analysis Results

The thermal analysis of the system is printed in monthly intervals with a yearly summary printed at the end. The results are an estimate of the system performance of a properly designed and installed system.

The definition of the six monthly output values follow.

SOLAR AVAIL. (GJ)

Total solar radiation incident on the collector over the time period in gigajoules.

SOLAR COLLECT (GJ)

Solar energy converted to heat by the solar collector over the time period.

HEATING LOAD (GJ)

The total energy required to heat the air from the ambient temperature to the drier inlet temperature.

AUX. HEATING (GJ)

Auxiliary energy required to heat the air over the time period when the solar heating system is used.

FAN POWER (GJ)

The electrical energy required to operate the collector fan over the time period.

MASS DRIED (KG) or TIME PERIOD (HOURS) is the total mass dried (based on dry weight) over the simulation period (if L1 = 0) or the time required to dry the mass (if L6 = 0).

After the monthly totals have been printed, the yearly sum of the six quantities is printed. A summary of energy use and savings is then printed in gigajoules.

The ENERGY SAVING DUE TO SOLAR is the percent reduction in auxiliary energy use attributable to the addition of the solar heating system i.e. percent solar. It is defined as:

$$\text{Energy Saving (\%)} = \frac{100\ (\text{Solar Energy Collected} - \text{Fan Power})}{\text{Heating Load}}$$

AVERAGE SOLAR SYSTEM COLLECTION EFFICIENCY (%) is the solar contribution (solar collected minus fan power) divided by the solar radiation over the simulation period. It is important to note that if the daily air flow schedule is very short this value will be low regardless of the collector performance curve.

SOLAR CONTRIBUTION PER SQUARE METRE is the solar contribution divided by the collector area over the simulation period. A good application of a solar drying system would have a value of over 1.0 GJ/m²/yr.

Two warnings may be printed at the end of the simulation.

DRIER COULD NOT MEET DRYING LOAD DURING TIME SPECIFIED ON __ DAYS. This warning applies only to constant drying quantity systems (L1≠0). It is the total number of days that the drier cannot dry the required quantity by midnight.

DRIER COULD NOT DRY MATERIAL TO VALUE OF L4 FOR __ HOURS. This is the number of hours that the outlet moisture content of the material can not achieve the value of L4. For these hours it is assumed that the drier does not operate.

5. PROGRAM ALGORITHM

5.1 Overview of Program Operation

The DRYAIR computer program calculates the performance of air-based solar collectors to dry crops or other materials on an hour-by-hour basis. The basic assumption of the program is that for the purposes of calculating performance all variables, including solar radiation, wet bulb temperature, dry bulb temperature and drying rate can be considered constant for each hour.

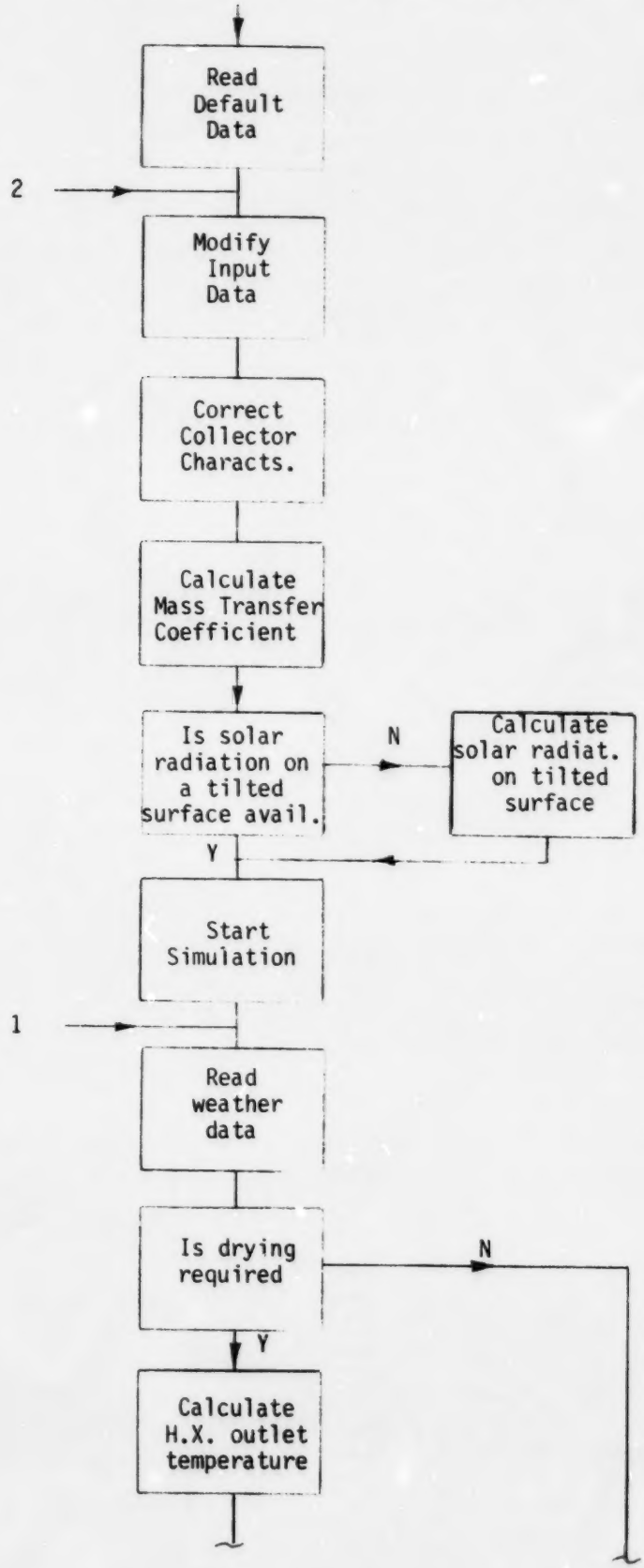
The program calculation flow chart is shown in Figure 2. The first step in the program is the input and modification of the program parameters in an interactive manner. Section 3 gives a full description of the input parameters.

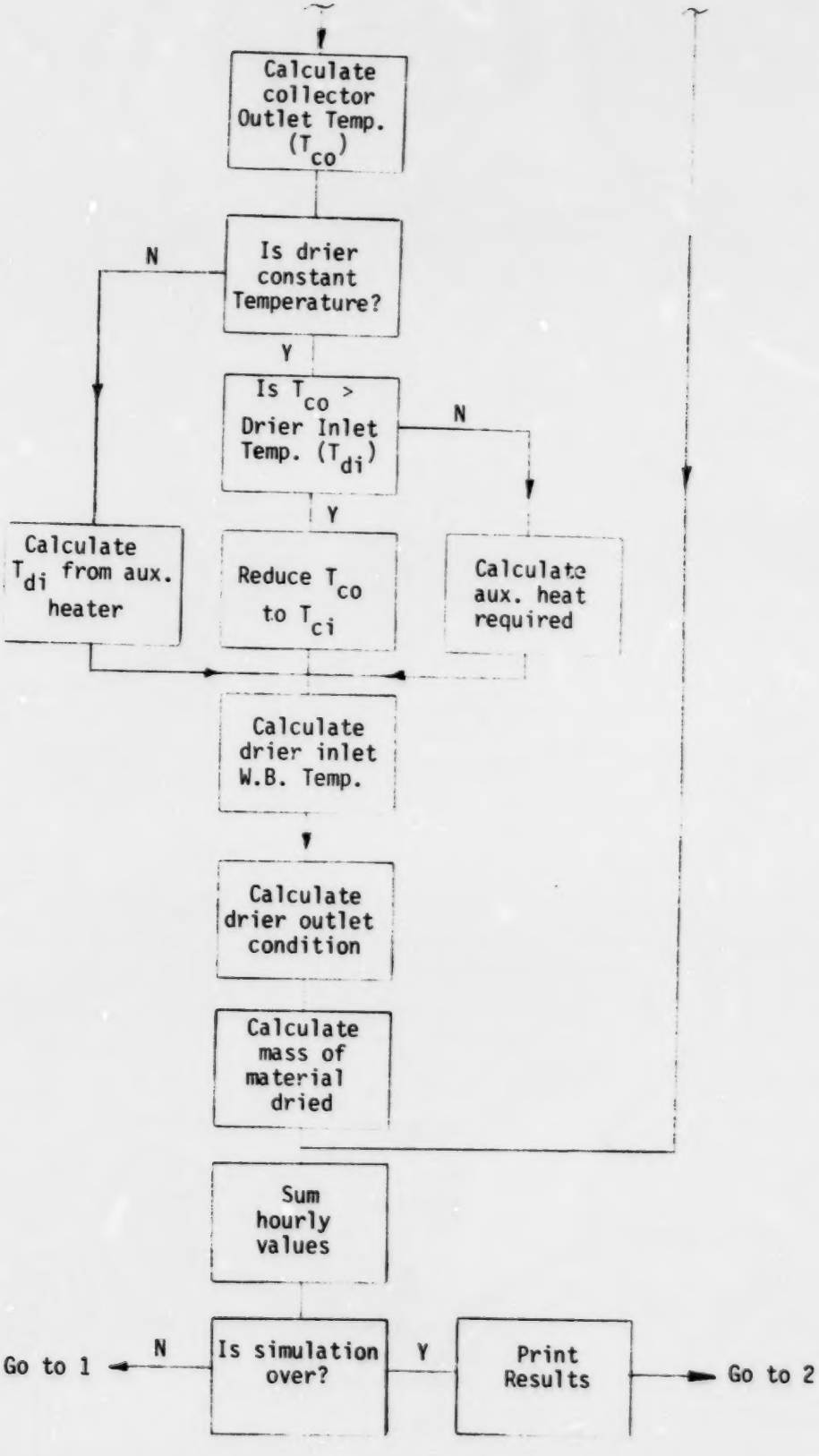
After all the parameters have been entered, the program calculates the collector heat removal factor for the test values of flow rate and flow path length using the method given in Section 5.2. This value is compared to the value of F_R found from the collector $F_R\tau\alpha$ term. The two values are printed at the terminal. At the test condition, the calculated value of F_R will be either higher or lower than the test value. If the difference between the values is greater than 20% the program prints a war ning and returns to the input mode.

If the collector slope or azimuth is different from the value used to calculate the solar radiation in the scratch file, the solar radiation on a tilted surface is recalculated. The algorithm for performing this calculation is given in Section 5.4.

The next step is to calculate the mass transfer coefficient for the drier based on the drier test data. This is an iterative procedure requiring making an estimate of the mass transfer coefficient and calculating the drier outlet air condition. The mass transfer coefficient is subsequently altered until the calculated outlet condition equals the test outlet condition. The

Figure 2: DRYAIR Program Flow Chart




Calculate collector Outlet Temp. (T_{co})
Is drier constant Temperature?
N
Y
Is T_{co} > Drier Inlet Temp. (T_{di})
N
Y
Calculate T_{di} from aux. heater
Reduce T_{co} to T_{ci}
Calculate aux. heat required
Calculate drier inlet W.B. Temp.
Calculate drier outlet condition
Calculate mass of material dried
Sum hourly values
Is simulation over?
N
Y
Go to 1
Print Results
Go to 2

algorithm for estimating the drier outlet condition from the inlet condition is given in Section 5.3.

When the solar radiation and input parameters are correct, the program begins the simulation. The first step is to calculate the properties of the outside air: humidity ratio and enthalpy. The humidity ratio (W) is given by:

$$W_{ai} = \frac{W_{s_w} h_{fg_w} - C_{p_a} (Ta_d - Ta_w)}{C_{p_w} (Ta_d - Ta_w) + h_{fg_d}} \qquad (5.1)$$

where Ta_d is the dry bulb ambient temperature,
Ta_w is the wet bulb ambient temperature,
C_{p_a} is the specific heat of air,
C_{p_w} is the specific heat of water,
h_{fg_w} is the latent heat of vapourization at the wet bulb temperature,
h_{fg_d} is the latent heat of vapourization at the dry bulb temperature,
W_{s_w} is the saturated humidity ratio at the wet bulb temperature given by:

$$\exp (-5.587 + 0.0761\ Ta_w - 0.000474\ Ta_w^2 + 3.93\times10^{-6}\ Ta_w^3) \qquad (5.2)$$

The enthalpy of the air is:

$$h_{ai} = C_{p_e} Ta_d + 2502.3\ W_{ai} \quad (KJ/kg) \qquad (5.3)$$

where C_{p_e} is the effective specific heat of the air

$$= C_{p_a} + C_{p_w} W_{a_i} - 2.425\ W_{a_i} \qquad (5.4)$$

If a heat exchanger is used before the collectors, the next step is to calculate the increase in air inlet temperature.

$$T_{hx_o} = T_{a_i} + E_{hx} (T_{do} - T_{a_i}) \qquad (5.5)$$

where E_{hx} is the effectiveness of the heat exchanger,
T_{hx_o} is the temperature out of the heat exchanger,
T_{do} is the temperature of the air leaving the drier (assumed to be equal to the drier inlet temperature).

The solar energy collected is calculated as:

$$Q_s = A_c \left[F_R\tau\alpha \; K \; H_T - F_R U_L \; (T_{hx_o} - Ta_d)\right] \tag{5.6}$$

where K is the incidence angle modifier factor = $1 + b_o(1/\cos\theta - 1.)$, (5.7)
H_T is the solar radiation on the collector,
A_c is the area of the collectors.

The collector outlet temperature is given by:

$$T_{co} = T_{hx_o} + Q_s \; / \; (C_{p_e} \; \dot{m}_a) \tag{5.8}$$

If the collector outlet temperature is greater than the maximum allowable temperature, it is assumed that some of the outside air bypasses the collector and is mixed with the collector outlet air. If a heat exchanger is placed after the collector the program calculates the change in air temperature using Equation 5.5 with T_{a_i} replaced with the collector outlet temperature. For the constant temperature drier, if the collector (or heat exchanger) outlet temperature is too cold, auxiliary heat is added to bring the air up to the desired temperature. For the constant heat input drier, the inlet temperature to the drier is:

$$T_{d_i} = T_{c_o} + Q_{heat} \; / \; (C_{p_e} \; \dot{m}_a)$$

If the drier inlet temperature exceeds the maximum allowable, the auxiliary heater is shut off.

The next step in the program is to calculate the wet bulb temperature at the drier inlet. This requires an iterative solution to equations 5.1 and 5.2. The drier inlet wet bulb temperature is used to calculate the saturated humidity ratio using equation 5.2.

When the drier inlet condition is known, the drier performance is calculated. The algorithm to estimate the drier outlet condition is given in Section 5.3. Knowing the amount of water that is removed, the quantity of material dried can be calculated:

$$\dot{m}_d = \frac{\dot{m}_a (Wa_o - Wa_i)}{(x_i - x_f)} \qquad (5.9)$$

where $\dot{m}_d$ is the rate of material drying,
x_i is the initial moisture content of the material,
x_f is the desired final moisture content of the material.

The hourly values of the above energy and mass flows are summed and monthly and yearly totals printed. A full description of the ouput is given in Section 4.

5.2 Algorithm for the Calculation of F_R

Two separate algorithms are used for the calculation of F_R, one for parallel plate solar collectors and one for fibre matrix solar collectors. It is important to note that a correction on F_R for the number of collectors in series is not necessary provided that the mass flow per unit area is kept constant.

i) F_R for Parallel Plate Solar Collectors

F_R is given by:

$$F_R = \frac{\dot{m}\, C_p}{U_L} (1 - \exp(-F' U_L / (\dot{m}\, C_p))$$

where $F' = U_o/(U_o + U_L)$

All of the variables are constant except for $\dot{m}$ (mass flow rate per unit area) and U_o (the total plate to fluid heat transfer coefficient). $\dot{m}$ is given each hour by the air flow rate schedule, thus, a new value of U_o must be calculated for each hour. U_o depends on the collector design.

The equations for U_o given below were taken from:

Hollands, K.G.T. and Shewen, E.C., Journal of Solar Energy Engineering, Vol. 103, No. 4, November, 1981. "Optimization of Flow Passage Geometry for Air-Heating, Plate-Type Solar Collectors".

$$U_o = h_{pf} + h_{pf} \; h_r/(h_r + h_{pf})$$

where h_r is the radiative heat transfer coefficient between the upper and lower absorber plates.

If we assume that the inside of the air channel is painted black:

$$h_r = \sigma(T_1^2 + T_2^2)\,(T_1 + T_2)/(1.222)$$

where T_1 and T_2 are the temperatures of the upper and lower absorber plates,

h_{pf} is the convective heat transfer coefficient between the plate and the air stream.

$$h_{pf} = Nu \;\; k/(2.b)$$

where k is the conductivity of air,

b is the spacing between the upper and lower absorber plates,

Nu is the Nusselt number.

for Re < 2000 (Reynolds number)

$$Nu = 5.385 + 0.148 \; Re \; b \; n/L$$

where n is the number of air flow passage channels (typically equal to 1),

L is the collector flow path length.

for 2000 < Re < 10000

$$Nu = 0.00044 \; Re^{1.2} + 9.37 \; Re^{0.471} \; b \; n/L$$

for 10000 < Re ≤ 100000

$$Nu = 0.03 \; Re^{0.74} + 0.788 \; Re^{0.74} \; b \; n/L$$

where $Re = \dfrac{2 \dot{m} L}{\mu}$

if Re is greater than 100000 the program sets Re equal to 100000.

ii) F_R for Fibre Matrix Collectors (see Figure 3)

The estimation of F_R for fibre matrix collectors requires a different formulation for F_R. F_R can be thought of as the ratio of the actual useful energy to the useful energy if the absorber plate were at the fluid inlet temperature (T_{fi}). For a ventilation collector F_R is:

$$F_R = \frac{\tau\alpha.I - U_L(T_{ave} - T_{fi})}{\tau\alpha.I - U_L(T_{fi} - T_{fi})} = 1 - \frac{U_L(T_{ave} - T_{fi})}{\tau\alpha.I}$$

where T_{ave} is the average temperature that the collector loses heat at. This temperature is normally the average plate temperature, however, a fibre matrix collector has inlet air blowing across the lower glazing thus loses heat from a lower temperature. For a fibre matrix collector T_{ave} is:

$$T_{ave} = (h_r\, T_{plate} + h_{pf}\, T_{fi})/(h_r + h_{pf})$$

where h_{pf} is the convective heat transfer coefficient between the lower glazing and the air stream,

h_r is the radiative heat transfer coefficient between the fibre matrix and the lower glazing. Because of the nature of the fibre matrix, h_r is a weighted average of the value of h_r for each layer of fibres with the top layer having a weighting of 1 and the bottom layer having a weighting of 0. By integrating the values of h_r over the depth of the matrix, h_r can be approximated by:

$$h_r = h_{r1}/3 + h_{r2}/6$$

where $h_{r1} = \sigma(T_1^2 + T_2^2)\,(T_1 + T_2)/1.222$

$h_{r2} = \sigma(T_{fo}^2 + T_2^2)\,(T_{fo} + T_2)/1.222$

T_1 is the temperature of the top of the fibre matrix,

T_2 is the temperature of the lower glazing.

The average fibre matrix plate temperature can be calculated by:

$$T_{plate} = T_{fm} + Qu/U_o$$

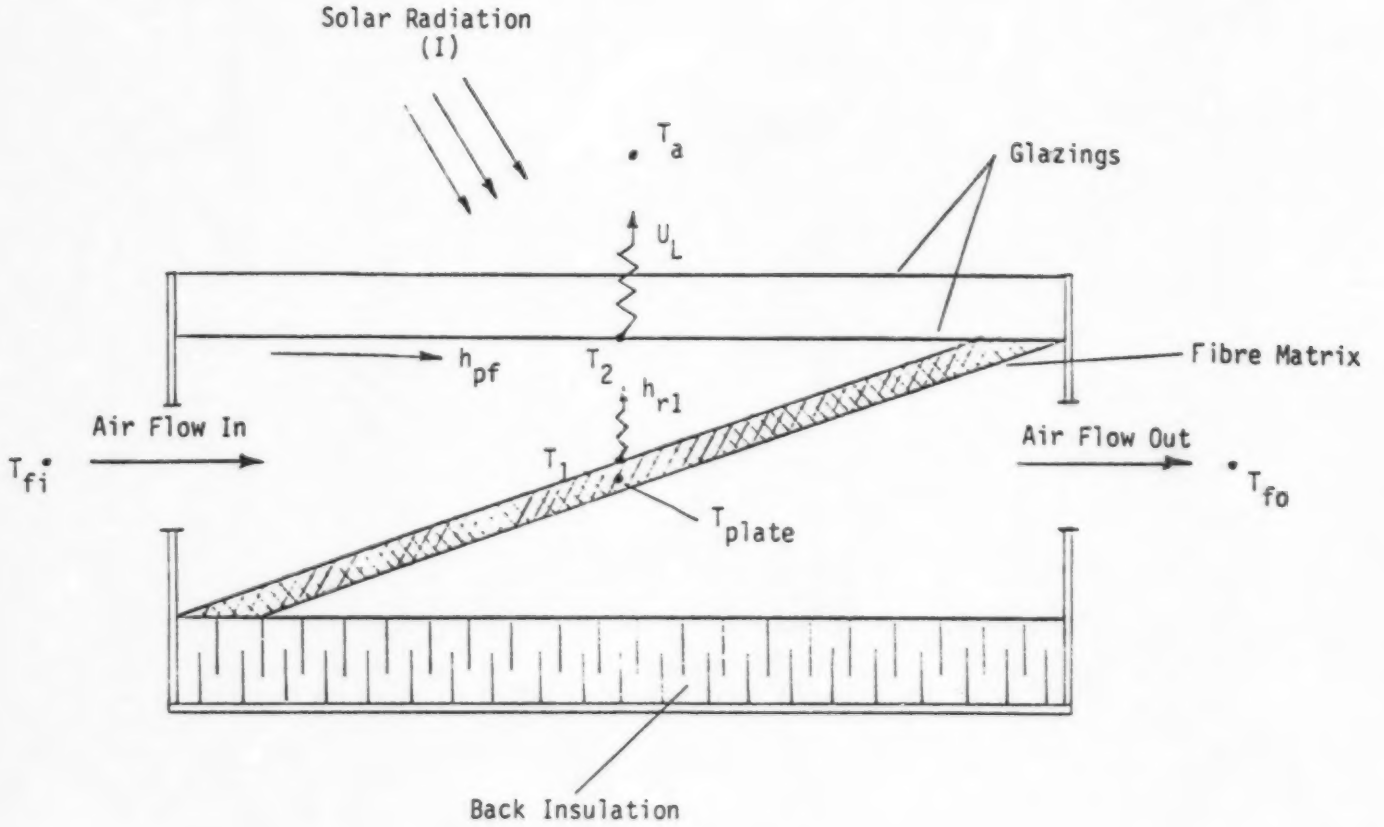


Figure 3: Schematic of Fibre Matrix Solar Collector

where U_o is the fibre matrix to air heat transfer coefficient,
T_{fm} is the average fluid temperature.

Estimating U_o for fibre matrix collectors is much more difficult than for parallel plate collectors. The reference used for these equations is:

Kays, W. and London, A.L., Compact Heat Exchangers, Second Edition, McGraw-Hill, New York, 1964, pg. 129.

For fibre matrices Kays and London give equations of the form:

$$U_o = x \left(\frac{A_{fm}}{A_c}\right) \dot{m} C_p / (Re^y \, Pr^{2/3})$$

where Pr is the Prandtl number,
x and y are constants dependent on the type and shape of the matrix.

For a similar type of fibre matrix Kays and London give:

$x = 1.3 \qquad y = 0.45$

By knowing the average fibre matrix diameter and the fibre matrix mass, the ratio of heat transfer to collector area can be calculated. For the Amherst collector

$$\frac{A_{fm}}{A_c} \cong 80.$$

5.3 Algorithm to Calculate Drier Performance

The program can simulate the performance of two types of driers: counter-flow and cross-flow. The theory of drying and the two types of driers are described below.

i) Drying Theory

The drying theory used in the program is based on the analysis by Threlkeld (2). Drying rate (R) is:

$$R = h_D (W_{s_w} - W)$$

where h_D is the mass transfer coefficient,
W_{s_w} is the saturated humidity ratio at the wet bulb temperature,
W is the humidity ratio of the air.

The mass transfer coefficient depends on many factors, however, the most important factor is the moisture content of the material. A typical curve for mass transfer coefficient versus material moisture content is shown in Figure 4. The mass transfer coefficient (and therefore the drying rate) is constant for moisture contents above a critical moisture content. At the critical moisture content, the rate of water migration from inside the material to the surface equals the rate of water evaporation. Below the critical moisture content, the mass transfer coefficient decreases as the moisture content decreases because water cannot be supplied fast enough to the material surface. The rate continues to decrease until the equilibrium moisture content is reached. At this point the drying rate is zero. Some researchers have suggested a drying curve with two regions (with different slopes) below the critical moisture content. It is unlikely, however, that the designer would have information on the drying rate for the two regions. Thus, for simplicity a single region drying curve is used by the program.

ii) Counter-Flow Drier

In a counter-flow drier the material and air move in parallel but opposite directions. The advantage of this design is that the driest air is in contact with the driest material. This arrangement allows the maximum amount of water to be transferred to the air.

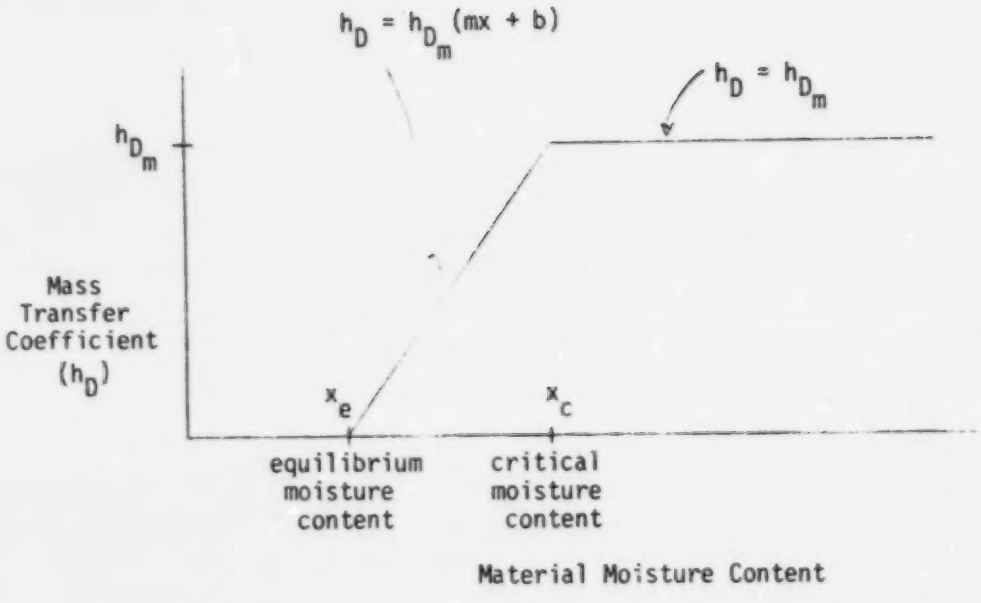


Figure 4: Typical Relationship between Mass Transfer Coefficient and Material Moisture Content

To determine the performance of this drier, the drying rate equation must be integrated over the length. In the drying rate equation h_D and W are changing as the air flows through the drier. This can be written as:

$$\dot{m}_a dW = R\, A_D\, M_D\, dL$$

where A_D is the drying area of the material,
M_D is the mass of the material,
L is the length of the drier.

This equation can be re-written as:

$$dL = \frac{\dot{m}_a\, d\, W}{A_D\, M_D\, h_D\, (W_{s_w} - W)}$$

The drier can be split into two regions: constant h_D and $h_D = h_{D_m}\,(mx + b)$, where h_{D_m} is the constant value of h_D above x_c (critical moisture content). The drier length can be split into these two regions.

$$L = L_1 + L_2$$

Constant h_D:

$$L_1 = \frac{\dot{m}_a}{A_D\, M_D\, h_{D_m}} \int_{W_c}^{W_o} \frac{d\, W}{(W_{s_w} - W)}$$

Variable h_D:

$$L_2 = \frac{\dot{m}_a}{A_D\, M_D\, h_{D_m}} \int_{W_i}^{W_c} \frac{d\, W}{(W_{s_w} - W)\,(mx + b)}$$

where $m = 1./(x_c - x_e)$
$b = -x_e/(x_c - x_e)$
where x_e is the equilibrium moisture content.

The solution to these equations is:

$$L_1 = \frac{\dot{m}_a}{A_D M_D h_{D_m}} \ln \left(\frac{W_{s_w} - W_c}{W_{s_w} - W_o} \right)$$

$$L_2 = \frac{\dot{m}_a}{A_D M_D h_{D_m}} Z_1 \left(\ln \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right) - \ln \left(\frac{Z_3 - Z_1}{Z_3 + Z_1} \right) \right)$$

where $Z_1 = (a_2^2 - 4a_1a_3)^{\frac{1}{2}}$

$Z_2 = 2a_3W_c + a_2$

$Z_3 = 2a_3W_i + A_2$

$a_1 = (mx_f - m\,\dot{m}_a\, W_i/\dot{m}_D + b)\, W_{s_w}$

$a_2 = m\,\dot{m}_a\, (W_{s_w} + W_i)/\dot{m}_D - mx_f - b$

$a_3 = - m\,\dot{m}_a/\dot{m}_D$

This equation must be solved iteratively for W_o and $\dot{m}_D$. The quantity $L\, A_D\, M_D\, h_D$ is a constant determined from the test results.

Most materials that are dried are relatively small in diameter (e.g. grains). The small diameter means that there is a large area for heat transfer. Thus, like a rock bed thermal storage unit, the air flowing through the drier becomes very close to the temperature of the material it is flowing through. For a counter-flow drier, this results in a stratified container with the grain in the bottom (i.e. inlet) half equal to the inlet air temperature and the air at the top (i.e. outlet) half equal to the grain temperature.

If the grain inlet temperature is not the same as the air inlet temperature, the air outlet temperature is reduced to the grain inlet temperature. The humidity ratio of the air is also reduced so as not to exceed 100% relative humidity at the new outlet temperature. Since most of the drying (i.e. water removal) occurs in the inlet half of the drier, the drying rate is not significantly affected by the grain inlet temperature.

ii) Cross-flow Drier

In a cross-flow drier the material and air flow in perpendicular directions. For the purposes of analysis the drier can be divided into two regions: constant mass transfer coefficient and variable mass transfer coefficient. The analysis of the constant mass transfer coefficient region is the same as for the counter-flow drier. For the variable region

$$\frac{A_D M_D}{L \dot{m}_a} = \int_{W_i}^{W_{o2}} \frac{d W}{h_D(W_{s_w} - W)}$$

Unlike the counter-flow drier, however, h_D does not vary in the flow direction. If an average h_D is used in the above equation, then the solution is the same as for the constant region.

The drier outlet humidity ratio is the weighted average of the outlet humidity ratio from the two drying regions (constant and variable h_D).

$$W_o = W_{o1} X + W_{o2} (1 - X)$$

where $X = Z/(1 + Z)$

$$Z = \frac{(x_i - x_c)(W_{o2} - W_i)}{(x_c - x_o)(W_{o1} - W_i)}$$

For cross-flow driers, if the grain inlet temperature is lower than the drier air inlet temperature, the drying rate is reduced. The reduction in drying rate is a result of a lower average air temperature and thus a lower water carrying capacity in the drier. To calculate the drying rate, the average drier air temperature based on the air and material flow rates is used.

5.4 Algorithm to Process Weather Data

Most Canadian weather stations measure only total solar radiation on a horizontal surface. Most solar collectors, however, are tilted toward the sun to increase the incident solar radiation. The program determines hourly values of total solar radiation (beam, diffuse and reflected) on a tilted surface and stores the values in a scratch file. The algorithm for converting horizontal solar radiation to tilted solar radiation is similar to the method used in "Solar Engineering of Thermal Processes" by Duffie and Beckman (2).

In order to estimate the solar radiation on a tilted surface it is necessary to split the total measured horizontal solar radiation into its two components: beam and diffuse. It is possible to estimate the amount of diffuse solar radiation from the ratio of the measured solar radiation to the extraterrestrial solar radiation. If this ratio is low then the solar radiation must be mostly diffuse; if this ratio is high the solar radiation must be mostly beam.

When the beam and diffuse solar radiation components are known, standard geometric relations can be used to estimate the solar radiation components on a tilted surface. When estimating solar radiation on a tilted surface a third component is introduced: reflected radiation. Reflected radiation can be estimated from the beam radiation and the ground albedo or reflectivity.

The program equations and execution procedure are given below.

At the start of each day the solar constant and the earth's solar declination are calculated. The solar constant is given by:

$$S_c = 4871.0\ (1. + 0.33\ \cos(2\pi N/365) \quad \text{in KJ/(hr m}^2\text{)}$$

where N is the day number (Jan 1 is 1).

The earth's declination is given by:

$$\delta = \frac{23.45 * 2\pi}{360} \sin\left(\frac{2\pi}{360}(284 + N)/365\right) \quad \text{(in radians)}$$

These values are assumed constant for each day. All other calculations are made on an hourly basis.

The first step is to read the measured weather values from the data file. For each hour the weather data file contains six values in the following order.

1) month number (1-12)
2) day number (1-31)
3) hour number (1-24)
4) ground reflectivity
5) solar radiation on a horizontal surace (in Watts/m^2)
6) ambient temperature (in °C)

The extraterrestrial solar radiation on a horizontal surface is calculated by:

$$H_{ex} = S_c \cos(\theta_z)$$

where $\cos(\theta_z)$ is cosine of the zenith angle (angle between the beam and the vertical.

$\cos(\theta_z) = \cos(\phi) \cos(\delta) \cos w + \sin\phi \sin\delta$

ϕ is the latitude of the location,

w is the hour angle.

The diffuse solar radiation (H_d) can be estimated using a correlation by Orgill and Hollands (3).

$$H_d = 0.1769\ H \qquad \text{if } 0.75 < K_T$$

$$H_d = (1.55699 - 1.84013\ K_T)\ H \qquad \text{if } 0.35 \leq K_T \leq 0.75$$

$$H_d = (1. - 0.248857\ K_T)\ H \qquad \text{if } 0.0 \leq K_T \leq 0.35$$

where H is the measured hourly solar radiation,

K_T is the ratio of measured solar radiation to the extraterrestrial solar radiation

$$K_T = H / H_{ex}$$

The beam radiation (H_b) is simply the total measured solar radiation minus the diffuse radiation.

$$H_b = H - H_d$$

The next step is to calculate the ratio of beam radiation on the tilted surface to that on the horizontal surace (R_b).

$$R_b = \cos(\theta_T)/\cos(\theta_z)$$

where $\cos(\theta_T)$ is the cosine of the angle of incidence of beam radiation, between the beam and the normal to the surface.

$$\cos(\theta_T) = [\sin(\delta)\ \sin(\phi)\ \cos(s)] - [\cos(\delta)\ \cos(\phi)\ \cos(s)\ \cos(w)] + [\cos(\delta)\ \sin(\phi)\ \sin(s)\ \cos(\gamma)\ \cos(w)] + \cos(\delta)\ \sin(s)\ \sin(\gamma)\ \sin(w)$$

γ is the azimuth angle measured from south (east is positive, west is negative).

Thus, the beam solar radiation on the tilted surface is

$$H_{bT} = R_b\ H_b$$

The diffuse solar radiation component on the tilted surface is estimated using the radiation view factor from the collector to the sky

with correction factors for non-uniform distribution of diffuse radiation.

The correction factors for anisotropic diffuse radiation are taken from Temps and Coulson (4) and Klucher (5). The resulting equation is:

$$H_{dt} = \left(\frac{1 + \cos(s)}{2}\right)(1 + F \sin^3(s/2))(1 + F \cos^2(\theta_T) \sin^3(\theta_z))\, H_d$$

where $F = 1 - (H_d/H)^2$

The reflected solar radiation on the tilted surface (H_r) is

$$H_r = \left(\frac{1 - \cos(s)}{2}\right) \rho\, H$$

where ρ is the ground reflectivity.

The total solar radiation on the tilted surface (H_T) is the sum of the beam diffuse and reflected solar radiation components.

Hourly values of total solar radiation on a tilted surface, ambient temperature, day number and hour number are written to the scratch file. When all the data has been processed and written to the scratch file, the file is rewound to be ready for the system simulation.

6. PROGRAM STRUCTURE

The program structure is described in this section. Only those individuals interested in modifying the program need read this section.

The program structure is shown in Figure 5. The program consists of a mainline and four subroutines:

1) MAINLINE - contains the interactive front-end for reading and modification of system data,
2) WEATH - subroutine for converting measured horizontal solar radiation to the tilted surface,
3) DRY - subroutine to calculate system performance on an hourly basis,
4) FRCALC - subroutine to calculate the collector heat removal factor F_R for a given flow rate,
5) DRIER - subroutine to calculate outlet humidity ratio from drier.

Six file definitions must be made before the program can be run:

Terminal (Read) - (Unit 5) is the device used for data input. The program will send all questions and prompts to this device.

Printer - (Unit 7) is the device that receives the printed output (i.e. a printer). If a send and receive printer is being used unit 7 need not be defined.

Weather Data - (Unit 2) is the file containing the TRNSYS compatible weather data. The data must be written in the format (2X, I2, 2X, I2, 2X, I2, F3.1, I3, F6.1) and contain month number, day number, hour number, ground reflectivity, ambient temperature (°C), and solar radiation on a horizontal surface (W/m^2).

Wet Bulb Data - (Unit 1) is the file containing the wet bulb temperatures. The data must be written in the Atmospheric Environment Service standard format (185 characters per line).

Processed Data - (Unit 19) is the file that is created by the program containing the solar radiation on the tilted surface and ambient temperature.

Terminal (Write) - (Unit 6) is the device that receives questions from the program concerning the input of data.

Default Data - (Unit 4) is the file containing program default data.

The DRYAIR program is written in FORTRAN 77. In order to compile this program on your system, it must be able to handle this improved version of FORTRAN.

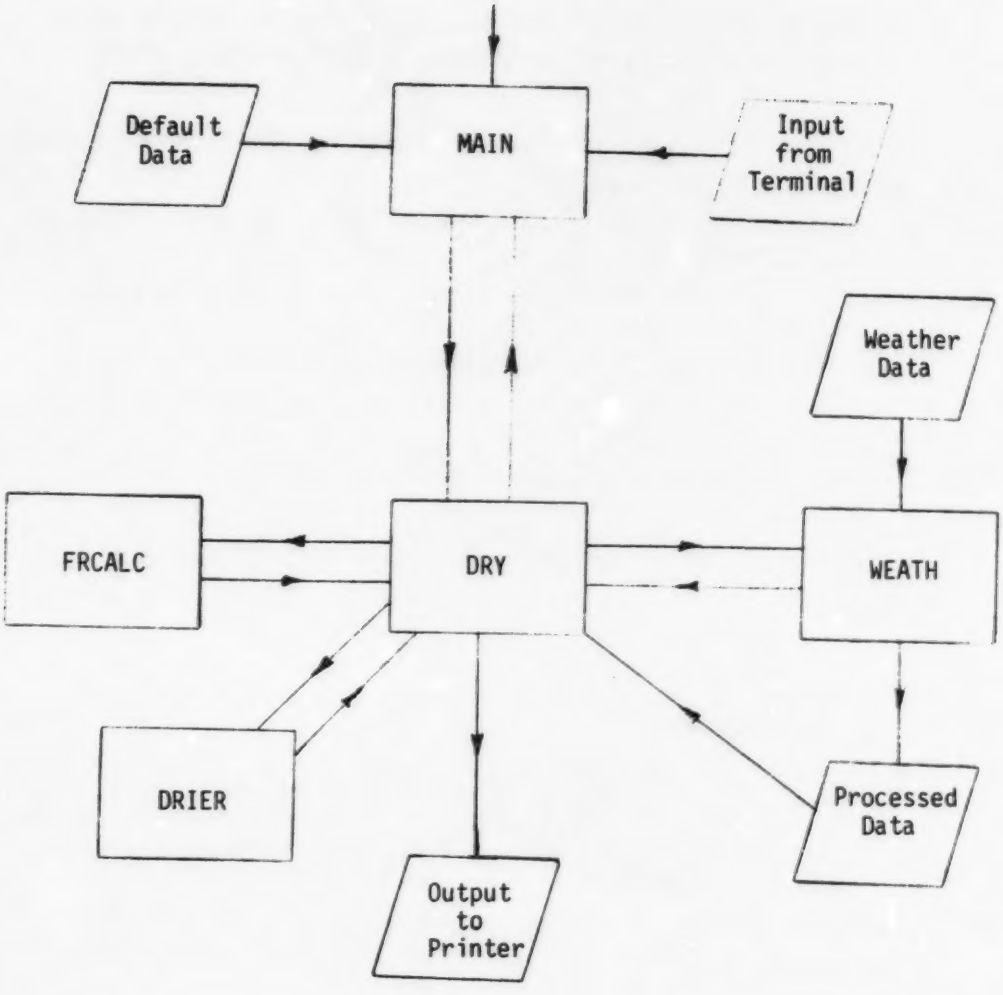


Figure 5: DRYAIR Program Structure

7. REFERENCES

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4. Orgill, J.F. and Hollands, K.G.T., Solar Energy, Vol. 19, No. 2, "Correlation Equation for Hourly Diffuse Radiation on a Horizontal Surface".

5. Temps, R.C. and Coulson, K.L., Solar Energy, Vol. 19, No. 2, "Solar Radiation Incident upon Slopes of Different Orientation".

6. Klucher, T.M., Solar Energy, Vol. 23, No. 2, "Evaluation of Models to Predict Insulation on Tilted Surfaces".

8. INPUT DATA WORKSHEET

		Default Value	
C.	COLLECTOR DATA		
C1	NUMBER OF COLLECTORS.....	20.00	_____
C2	NUMBER OF COLLECTORS IN SERIES.....	1.00	_____
C3	COLLECTOR SLOPE (DEGREES).....	45.00	_____
C4	COLLECTOR ORIENTATION (SOUTH=0,EAST=+, DEG.)....	.00	_____
C5	COLLECTOR FLOW RATE PER UNIT AREA (L/(SEC*M2))..	10.00	_____
C6	FAN POWER CONSUMPTION PER UNIT AREA (W/M2).....	10.00	_____
T.	COLLECTOR TEST DATA		
T1	GROSS AREA OF ONE COLLECTOR (M2).....	2.00	_____
T2	NUMBER OF COLLECTORS IN SERIES WHEN TESTED.....	1.00	_____
T3	FR-TAU-ALPHA (TEST).....	.50	_____
T4	FR-UL (W/(M2*C)) (TEST).....	4.00	_____
T5	INCIDENT ANGLE MODIFIER	-.10	_____
T6	COLL. TEST FLOW RATE PER UNIT AREA (L/(SEC*M2)..	10.00	_____
T7	TRANSMISSION-ABSORPTION PRODUCT	.90	_____
T8	RATIO OF APERTURE TO GROSS AREA	.90	_____
T9	COLLECTOR CHANNEL HEIGHT (MM).....	6.00	_____
T10	COLLECTOR FLOW CHANNEL LENGTH PER COLLECTOR (M).	1.00	_____
M.	MATERIAL DRYING CHARACTERISTICS		
M1	% EQUIL. MOISTURE CONTENT AT 10 RH AIR (DRY WT.)	3.00	_____
M2	% EQUIL. MOISTURE CONTENT AT 70 RH AIR (DRY WT.)	10.00	_____
M3	% CRITICAL MOISTURE CONTENT (DRY WT.).....	40.00	_____
M4	SPECIFIC HEAT OF DRY MATERIAL (KJ/(KG*C)).....	2.00	_____
L.	DRYING LOAD DATA		
L1	MASS OF MATERIAL TO BE DRIED (KG-DRY/DAY),0=MAX.	.00	_____
L2	% INLET MOISTURE CONTENT (KG-WATER/KG-DRY MAT.).	70.00	_____
L3	INLET TEMPERTURE OF MATERIAL (C).....	20.00	_____
L4	% OUTLET MOISTURE CONTENT (KG-WATER/KG-DRY MAT.)	20.00	_____
L5	NUMBER OF DAYS OF OPERATION PER WEEK.....	7.00	_____
L6	HOURS OF OPERATION PER DAY, 0=REQUIRED TIME.....	8.00	_____
L7	STARTING HOUR FOR DRYING OPERATION.....	8.00	_____

D. DRIER CHARACTERISTICS

D1	DRIER DESIGN : 1 - COUNTER-FLOW, 2 - CROSS-FLOW	1.00
D2	TYPE : 1-CONSTANT ENERGY INPUT, 2-CONSTANT TEMP.	2.00
D3	MAXIMUM AIR INLET TEMPERATURE (C).....	30.00
D4	IF D2=1, AUX. HEATER OUTPUT (KW).....	10.00
D5	DRIER H.X. LOCATION 0=NONE,1-BEFORE,2-AFTER COL.	.00
D6	EFFECTIVENESS OF DRIER HEAT EXCHANGER.....	.00
D7	DRIER TEST FLOW RATE (M3/S).....	1.00
D8	DRIER TEST INLET TEMPERATURE (C).....	20.00
D9	TEST INLET RELATIVE HUMIDITY (%).....	20.00
D10	TEST OUTLET RELATIVE HUMIDITY (%).....	70.00

APPENDIX A: EQUILIBRIUM MOISTURE RELATIONSHIPS FOR CERTAIN CROPS taken from the 1977 Ashrae Handbook of Fundamentals